

# Are Super-Luminous supernovae and Long GRBs produced exclusively in young dense star clusters?

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## ABSTRACT

In the last few years new classes of extremely bright supernovae have been discovered, but their rates are so small that models either fail to produce any or dramatically over-produce the event rates. These super-luminal supernovae tend to occur almost exclusively in relatively low-mass galaxies that undergo active star formation. In the same type of galaxies another high energy phenomenon occurs, which are the long-duration gamma ray bursts, which are associated with another type of very energetic supernovae, the SN Ic-peculiar. We argue that both the super luminal supernovae and the long-duration GRBs are exclusive products of dynamical interactions and collisions in young dense star clusters, which are abundant in dwarf galaxies with active star formation. We present a model that explains how these different types of explosive events can be produced and show that this model can explain their observed rates. In our model the different types of super luminal supernovae and the long-duration gamma-ray bursts are related, in being a natural consequence of the dynamical evolution of dense star clusters.

*Subject headings:* gamma-ray burst: general – supernovae: general – globular clusters: general – galaxies: star clusters – galaxies: starburst

## 1. Introduction

In the past decades several new and rare types of extremely bright and peculiar supernovae have been discovered: (i) The broad-line Type Ic-peculiar supernovae that are associated with long-duration GRBs (“long GRBs” hereafter). These were the first new and extremely bright type of supernovae discovered (Galama et al. 1998; Gehrels & Mészáros 2012). They have no H and He in their spectra and are characterized by extremely large outflow velocities ( $\sim 40,000$  km/s), implying very large kinetic energies ( $\sim 10^{52}$  ergs). They are related to the explosions of rapidly rotating pure Carbon-Oxygen (CO) stars with masses  $\gtrsim 5 M_{\odot}$  Cano et al. (2011) — bare cores

of originally very massive stars, and the prototype SN1998bw/GRB980425 ejected of order half a solar mass of  $\text{Ni}^{56}$  (Iwamoto et al. 1998; Cano et al. 2011). (ii) The so-called Super-luminous Supernovae (SLSN), a new class of supernovae discovered with the recent large-scale surveys for transients. The several tens of extremely energetic and bright SLSNe have bolometric luminosities up to some 50 times those of type Ia supernovae (Gal-Yam 2012). There are at least three classes of SLSN: the SLSN-I which lack hydrogen in their spectra, the SLSN-II which do have H in their spectra and the SLSN-R which have a long light-curve tail powered by the radioactive decay of a large amount ( $\sim 5 M_{\odot}$ ) of  $\text{Ni}^{56}$  (see

Gal-Yam (2012) for a review). Both the SLSN and the long GRBs with their Type Ic-peculiar SNe have in common that: (1) They are extremely rare: The rate of long GRBs ( $10^{-7}/\text{Mpc}^3/\text{yr}$ ) is some  $10^3$  times lower than the core-collapse SN rate. The combined rate of the SLSN is of order  $10^{-8}/\text{Mpc}^3/\text{yr}$ , some  $10^4$  times lower than the core-collapse SN rate, which imply that an extremely rare type of stellar evolution is required to produce these types of events (see Tab.1). (2) Both the long GRBs and SLSN occur almost exclusively in small star-forming galaxies (SMC/LMC-like or smaller). Only one in a representative sample of 42 long-GRBs is hosted by a grand-design spiral galaxy, and all the 41 others fall on optically bright spots of small star-forming galaxies (Fruchter et al. 2006). Studies of nearby small star-forming galaxies show that such bright spots are clumps of massive O- and Wolf-Rayet (WR) stars. For example NGC 3125 has a number of such clumps that show a mixture of O- and WR spectra (Hadfield & Crowther 2006). Studies of these clumps show that such small galaxies may harbor as many as  $10^4$  O- and WR stars, which are concentrated in a small number (3 to 6) young massive star clusters.

## 2. The connection between super-luminal supernovae and long gamma-ray bursts

The SLSN share the property of the long GRBs to occur almost exclusively in small star-forming galaxies. The only two SLSN-II that reside in larger Milky-Way-type galaxies were found very close to the nucleus of their hosts and (Gal-Yam 2012) remarks that this “*suggests that to produce SLSN perhaps special conditions are required that are unique to this environment (e.g. circum-nuclear star-forming rings), somehow mimicking the conditions in star-forming dwarf galaxies.*” Indeed, the inner few hundred parsecs of the bulges of most spiral galaxies are undergoing nuclear starbursts. Seyfert galaxies, and even the Milky-Way Galaxy, are prime examples (Conti et al. 2008). Within 100 pc from the center of the Milky-Way Galaxy many dense young massive star clusters are present, of which the Arches and Quintuplet clusters are the most prominent, both hosting  $> 10^4$  stars (Figer 2004). Even more important than mass (as we will argue below) is their very high stellar density, which in the center of

Arches exceeds  $10^5 M_{\odot}/\text{pc}^3$ . Such a high stellar density seems to be also a characteristic of the young clusters in small star-forming galaxies like the LMC, where for example the central part of the R136 cluster has such a high density (Andersen et al. 2009). The reason for the clusters in small star-forming galaxies to have such high stellar densities may be related to the turbulent velocity structure which leads to a shorter free-fall timescale of the gas than in the disks of large galaxies (Elmegreen et al. 2012). We suggest that the dense torus of in-spiralling gas accumulating in the central few hundred pc of the bulges of spiral galaxies may also have a turbulent velocity structure, due to the high local star formation and associated high supernova rate.

It thus appears that both the long GRBs/Type Ic-peculiar SNe and the SLSN solely occur in regions of galaxies where dense young massive star clusters are present. This strongly suggests that both types of objects are the products of evolutionary processes that are unique to young massive star clusters, and do not occur anywhere else (such a suggestion was casually made to one of us in 2006 for long-GRBs by S.R. Kulkarni).

### 2.1. Conditions required for producing long GRBs

The general consensus is that the condition required for producing a long GRB is: the collapse of a rapidly rotating practically bare CO-core of a massive star. There is strong observational evidence that the GRB is produced by a narrowly collimated relativistic jet with a Lorentz-factor of order  $10^2$  to  $10^3$  (Gehrels & Mészáros 2012). There are two models for producing such jets: (i) The collapsar model of (Woosley 1993), in which a very massive rapidly rotating core collapses to a black hole, but the core has so much angular momentum that not all of the core matter can at once disappear into the black hole, and part of the core matter temporarily forms a disk of nuclear matter around the black hole. Viscous and/or magnetic dissipation on this disk drives a relativistic jet which produces the GRB (MacFadyen & Woosley 1999); (ii) An alternative collapse model is one in which the rapidly rotating core collapses to an unusually strongly magnetized neutron star (magnetar) that is spinning with a period of order of a millisecond. The spin-down energy loss by mag-

netic dipole emission and the relativistic wind of such an extreme pulsar is so gigantic that it will spin-down to long periods on a timescale of minutes to hours and produce energetic electromagnetically powered relativistic jets along the rotation axis (Woosley 2010; Kasen & Bildsten 2010; Gehrels & Mészáros 2012).

Both these models require that in order to produce a long GRB, the collapsing massive CO core must have very high angular momentum (Woosley & Bloom 2006). Two possible ways have been suggested for the core of a massive star to keep high angular momentum throughout its life, either (a): very low metallicity (e.g. Yoon & Langer (2005)) or (b) evolution in a close binary system (e.g. van den Heuvel & Yoon (2007); Fryer et al. (2007)). In the first type of models it is argued that low metallicity gives weak stellar winds such that the winds do not carry off much angular momentum and the star keeps high angular momentum throughout its life. Its rapid rotation, in these models, keeps the star completely mixed, such that it evolves homogeneously and may in the end become a rapidly rotating CO star that collapses. However, the requirement of very low metallicity is not fulfilled for many of the host galaxies of long GRBs, because their metallicities turn out to range from  $0.01 Z_{\odot}$  all the way to  $Z_{\odot}$  (Wolf & Podsiadlowski 2007; Gehrels & Mészáros 2012). Therefore low metallicity cannot be the defining cause of the occurrence of long GRBs, since whether or not a long GRB will occur in a galaxy appears not to be strongly dependent on its metallicity.

In close binary models tidal forces keep the star in synchronous (rapid) rotation (van den Heuvel & Yoon 2007), or a rapidly rotating merger product is produced (Helium merger GRB; Fryer et al. (2007)). The first model has great difficulty reaching the specific angular momentum required for making a long GRB, and may only do so in very special cases (e.g. van den Heuvel & Yoon (2007)). Since massive binaries are found throughout the disks of spiral galaxies, both models, even if they could succeed, would be expected to produce many long GRBs in disks of spirals, contrary to the observations.

While normal close binary evolution, including tidal synchronization, may not be able to reach and maintain the specific angular momentum re-

quired for producing a GRB, a CO-core produced in an off-center collision of two evolved massive stars in a dense cluster, may have very high angular momentum, sufficient to produce a GRB.

### 3. The link with dense young star clusters

The majority of massive stars form in dense clusters. The most massive star  $m_{\max}$  in a cluster of mass  $M_{\text{cl}}$  is  $m_{\max} \simeq 1.2(M_{\text{cl}}/M_{\odot})^{0.45} M_{\odot}$  (Weidner & Kroupa 2004) with a maximum of about  $150 M_{\odot}$  (Figer 2005). Such a star sinks to the cluster center by dynamical friction in a small fraction ( $\langle m \rangle / m_{\max}$ ) of the two-body relaxation timescale  $t_{\text{rlx}}$ , although the star cannot reach the cluster center within its own orbital time scale in the potential of the cluster.

Massive stars (of  $m_{\text{ZAMS}} \gtrsim 25 M_{\odot}$ ) develop massive CO-cores ( $m_{\text{co}} > 4 M_{\odot}$ ) near the end of their fuel processing lifetime; we calculate the moment until the CO core develops by performing a series of simulations using the MESA stellar evolution code (Paxton et al. 2011) within the AMUSE framework (Portegies Zwart et al. 2013), and this fits

$$t_{\text{co}} \simeq 52(m_{\text{ZAMS}}/M_{\odot})^{-0.635} [\text{Myr}]. \quad (1)$$

For a sufficiently dense cluster,  $t_{\text{co}}$  of the most massive star is longer than the dynamical friction time scale, and the star develops a CO core after it arrives in the cluster center. Many of these massive stars are born in close binary systems (Sana et al. 2012), the majority will evolve according to regular Roche-lobe overflow. A single massive star, or one in a binary system, will upon arrival in the central portion of the star cluster, acquire a companion to form a binary or triple system (Heggie et al. 1996). A newly formed binary will at first be rather wide, with a binding energy comparable to the mean kinetic energy of the stars, or  $\sim 1\text{kT}$ . Repeated interactions with other cluster members drive the hardening of the binary to  $\gtrsim 100\text{kT}$  in  $\lesssim 0.2 t_{\text{rlx}}$  (Portegies Zwart & McMillan 2002). A side effect of this hardening process, mediated by exchange interactions, is the ejection of massive stars with high velocity as OB runaways (Fujii & Portegies Zwart 2011). This hardening process eventually causes the two most massive stars in the cluster to occupy the same binary

(Gaburov et al. 2008), although more bodies are involved in the process (Tanikawa et al. 2012).

The chance of a traffic accident during the quick dynamical evolution of this central sub-system is very large, in particular if the configuration resembles a hierarchical system in which the two most massive stars are in a relatively tight binary that is orbited by a less massive outer star. Such systems with inclination  $i \gtrsim 50^\circ$  are known to be subject to the Kozai effect (Kozai 1962), in which the exchange of angular momentum between an inclined outer orbit and the tight inner orbit drives the latter to extremely high ( $\gtrsim 0.9$ ) eccentricity. The time scale for the Kozai cycles (Kinoshita & Nakai 1999) is much shorter than the core relaxation time of the cluster, and the two inner stars eventually experience a collision.

The consequence of a collision depends on the evolutionary states of both stars. If sufficiently close in mass, the two stars could both have simultaneously well developed CO cores. A dynamical (or Kozai-driven) off-center collision between these stars results in common-envelope evolution in which the two CO-cores spiral towards each other and the collision energy combined with the released orbital binding energy drive off the H- and He- envelope. Mergers of the two inspiralling CO cores produces a critically rotating massive CO-star which resembles the progenitor of a long GRB (Cano et al. 2011). During the explosion of the  $\gtrsim 5 M_\odot$  rapidly rotating helium depleted merger product, a considerable amount of  $\text{Ni}^{56}$  is expected to be ejected in a Type Ic-peculiar supernova (Cano et al. 2011).

The time interval in which the star has a CO core, however, is extremely short, and at first glance it seems unlikely to have both stars of an interacting binary in this state. The cluster, however, assists here in bringing the two most massive stars together in a binary star. The lifetime of the CO core ( $m_{\text{co}} \gtrsim 4 M_\odot$ ) of a massive  $m_{\text{zams}} \gtrsim 25 M_\odot$  star is 4000 to 14000 years. We constrain the duration between the development of the CO-core and the moment of the supernova with the earlier mentioned simulations, and find it to fit

$$dt_{\text{co}} \simeq 0.15 (m_{\text{zams}}/M_\odot)^{-0.70} [\text{Myr}]. \quad (2)$$

Inverting Eq. 2 gives the allotted range in masses between primary and secondary star for

which both have a well developed CO core at the same time. By integrating the initial stellar mass function (Kroupa & Weidner 2003) we calculate the probability that two stars in a cluster of mass  $M_{\text{cl}}$  both have a massive CO core. The integration was performed by adopting a Schechter function (Schechter 1976) for clusters masses with a minimum mass of  $M_{\text{cl}} = 10^3 M_\odot$  and a characteristic mass of  $10^6 M_\odot$ . To bracket the event rate for the Milky-Way Galaxy we also integrate over a distribution of cluster radii. For the size distribution of the clusters we fitted the observed distribution of cluster sizes (taken from Tabs 2, 3 and 4 of Portegies Zwart et al. (2010)) to a log-normal distribution, which gave a satisfactory fit for a mean radius of 5 pc and a dispersion of 3 pc.

#### 4. Event rates for SLSN and GRBs in young star clusters

Normalized to the core-collapse supernova rate (derived from counting the number of stars between 8 and  $25 M_\odot$ ) we then obtain a relative frequency of  $\mathcal{R}_{\text{Ic-p}} \simeq 1.1 \cdot 10^{-4}$ , which is very low compared to the observed rate of  $\mathcal{R}_{\text{Ic-p}} \simeq 10^{-3}$  (Galama et al. 2000). The rate in blue-compact dwarf galaxies may be higher due to the over abundance of relatively low-density star clusters in the Milky-Way Galaxy, which we used to constrain the size distribution of the star clusters in our simulations. Reducing cluster radii to a mean of 2 pc but keeping the same dispersion in the log-normal distribution results in a rate of  $\mathcal{R}_{\text{Ic-p}} \lesssim (0.14 - 14) \cdot 10^{-3}$ , which brackets the observed rate. Here the strict upper limit is calculated by allowing also less massive stellar pairs (but with  $m_{\text{CO}} > 4 M_\odot$ ) to contribute to the supernova type Ic-peculiar rate. This derived rate brackets the observed rate and is consistent with the observed rate for long GRB (Gal-Yam 2012). We summarize the observed and our derived rates in Table 1. With the same integration we calculated that stars with  $m_{\text{ZAMS}} \gtrsim 25 M_\odot$  collapse in a type Ibc supernova at a rate of  $\mathcal{R}_{\text{Ibc}} = 0.25 \pm 0.01$ , which is consistent with the observed rate of  $\mathcal{R}_{\text{Ibc}} \simeq 0.22 \pm 0.06$  (Cappellaro et al. 1999).

The above scenario does not work for clusters that experience core collapse before the first supernova, because this will initiate a collision runaway producing a supermassive star

(Portegies Zwart & McMillan 2002). This process is arrested by stellar-wind mass loss and the first supernova. The amount of mass that is accumulated in the collision runaway product depends on the time of core collapse compared to the lifetime of the most massive star (Portegies Zwart et al. 2006). As a consequence, the event rate depends on cluster mass and size.

The collision rate during the time between core collapse and the supernova explosion of the collision runaway product determines the maximum mass of the latter (Portegies Zwart & McMillan 2002). In relatively low-mass star clusters  $M_{\text{cl}} \simeq 10,000 M_{\odot}$  to  $30,000 M_{\odot}$  the collision runaway product can reach a mass of  $150 M_{\odot}$  to  $260 M_{\odot}$  (Portegies Zwart & van den Heuvel 2007). These stars collapse in a luminous electron-capture supernova (Scannapieco 2009; Cooke et al. 2012), giving rise to a SLSN-R, as these supernovae produce large amounts of  $\text{Ni}^{56}$ , like was proposed for SN2007bi by Pan et al. (2012).

Only the densest (virial radius  $\lesssim 0.3 \text{ pc}$ ) star clusters contribute to this rate. An environment with a larger proportion of dense and massive clusters, like in blue-compact dwarf galaxies, will have a higher proportion of SLSN-R compared to core collapse supernovae. For the cluster size distribution as observed in the Milky-Way Galaxy we calculated a rate of  $\mathcal{R}_{\text{SLSN-R}} \lesssim 2.3 \cdot 10^{-6}$ , which is much lower than the observed rate of  $\mathcal{R}_{\text{SLSN-R}} = 2 \cdot 10^{-5}$ . The rate we derive for the population of blue-compact dwarf galaxies is  $\mathcal{R}_{\text{SLSN-R}} \simeq 2.1 \cdot 10^{-5}$ , which is close to the observed rate.

In clusters of  $> 30,000 M_{\odot}$ , if sufficiently dense the collision runaway can grow to a mass  $> 260 M_{\odot}$ . We suggest that these “super stars” produce SLSN-I/II by collapsing to a black hole of intermediate mass Scannapieco (2009). The mass of the collision runaway can reach values of up to a few  $10^3 M_{\odot}$  (Portegies Zwart & McMillan 2002). By the time the star experiences a supernova it has shed most of its mass again in a dense stellar wind (Yungelson et al. 2008) and it is uncertain how much mass eventually collapses to the black hole. Integrating over the mass and size distributions for star clusters we derive a rate of  $\mathcal{R}_{\text{SLSN-I/II}} \simeq 6.1 \cdot 10^{-5}$  for the Milky-Way population. By adopting the same size distribution and mass distribution of star clusters as

we did before for the population of clusters in blue-compact dwarf galaxies we arrive at a rate of  $\mathcal{R}_{\text{SLSN-I/II}} \simeq 1.8 \cdot 10^{-4}$ , which again is similar to the observed rate for combined types SLSN-I and SLSN-II.

We do not make the distinction between type SLSN I and type II here but derive the total rate. Upon each collision several  $M_{\odot}$  of hydrogen is injected into the collision runaway, but this mass is blown away in the copious stellar wind in a few  $10^4$  years. A collision between the runaway and a hydrogen rich star shortly before the supernova of the former was proposed by (Portegies Zwart & van den Heuvel 2007) to explain the SLSN-II 2006gy which occurred close to the nucleus of a large galaxy (Quimby 2006). The ratio between the timescale on which fresh hydrogen is injected into the collision runaway and the time required to deplete the newly acquired hydrogen envelope determines the ratio of SLSN type II relative to SLSN type Is. The observed comparable rates of type SLSN-II relative to SLSN-I is consistent with this regime of collisional growth (Portegies Zwart & McMillan 2002). Both the rates for SLSN-R and for SLSN-I/II increase if a higher proportion of star clusters are born with high density, like is the case for clusters in blue-compact dwarf galaxies compared to the Milky-Way.

In the collapsed core of a dense young star cluster an intermediate mass a black hole is likely to be accompanied by another star, or otherwise it will acquire one within a core relaxation time scale. The orbital period of such a binary typically is in the range of 50 to 500 days (Patruno et al. 2006). Once the captured companion overfills its Roche-lobe and transfers mass to the intermediate-mass black hole the binary becomes visible as an ultra luminous x-ray source, much like the observed systems M82 X-1 (Kaaret et al. 2001), NGC1313 X-2 (Zampieri & Patruno 2011) and HLX-1 (Webb et al. 2012), NGC5408 X-1 (Strohmayer 2009) and NGC7479 X-1 (Voss et al. 2011). The observed periodicity in M82 X-1 (62 days), NGC5408 X-1 (115days) and HLX-1 (388days) and their x-ray fluxes are consistent with a cluster member being captured by an intermediate mass black hole and feeding the latter via a dense stellar wind or Roche-lobe overflow (Patruno et al. 2006). We expect such objects to

reside in clusters of  $> 30,000 M_{\odot}$ .

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Table 1: Event rates for the families of supernovae. Observed rates (second column) are from (Gal-Yam 2012). The rates are normalized to the core collapse supernova rate, which for the simulations was calculated self-consistently. The best values are from our adopted Schechter mass function with a characteristic mass of  $10^6 M_\odot$  and with a log-normal size distribution with mean of 2 pc, which represents the star clusters in blue-compact dwarf galaxies. The rates for the Milky-Way are calculated for a sample of young star clusters consistent with those observed in the local group.

SN type	observed	model	model
		best value	Milky-Way
SN Ibc	0.22	0.25	0.25
SN Ic-peculiar	$1 \cdot 10^{-3}$	$(0.14-14) \cdot 10^{-3}$	$1.1 \cdot 10^{-4}$
SLSN-I/II	$1.7 \cdot 10^{-4}$	$1.8 \cdot 10^{-4}$	$6.1 \cdot 10^{-5}$
SLSN-R	$2 \cdot 10^{-5}$	$2.1 \cdot 10^{-5}$	$2.3 \cdot 10^{-6}$